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Nucleus–nucleus collisions at high baryon densities

H. Weber, E.L. Bratkovskaya [1], H. Stöcker

Institut für Theoretische Physik, Universität Frankfurt, 60054 Frankfurt, Germany

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Abstract

We study central collision of Pb + Pb at 20, 40, 80 and 160 A GeV within the UrQMD transport approach and compare rapidity distributions of π^-, K^+, K^- and Λ with the recent measurements from the NA49 Collaboration at 40, 80 and 160 A GeV. It is found that the UrQMD model reasonably describes the data, however, systematically overpredicts the π^- yield by $\sim$20%, whereas the K^+ yield is underestimated by $\sim$15%. The K^- yields are in a good agreement with the experimental data, the Λ yields are also in a reasonable correspondence with the data for all energies. We find that hadronic flavour exchange reactions largely distort the information about the initial strangeness production mechanism at all energies considered.

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The dynamics of nucleus–nucleus collisions at high baryon density—contrary to the high energy density at RHIC and LHC—is of present interest with respect to the parton/hadron phase transition at high quark chemical potential. Furthermore, as has been proposed early by Rafelski and Müller [1] the strangeness degree of freedom might play an important role in distinguishing hadronic and partonic dynamics. This also relates to the entropy per baryon (or number of constituent quarks) which provides information on the effective number of degrees of freedom involved. Additionally, one expects that at high net quark density the chiral symmetry of QCD—which is broken in the vacuum as reflected in the non-vanishing quark condensate $\langle \bar{q}q \rangle$—becomes restored for considerable space–time intervals (cf. Figs. 3, 4 in [2]). Thus the (at least partial) restoration of chiral symmetry should lead to dramatic changes of the hadron spectral functions, which either might show poles at zero masses [3] or a complete mixing for chiral partners such as the ρ- and a_1-mesons [4,5]. The related questions are addressed in more detail in the proposal for the (discussed) future heavy-ion facility at GSI Darmstadt [6].

Whereas experimentally the dynamics of heavy nucleus–nucleus collisions have been studied up to 11.6 A GeV at the BNL AGS and an extensive program has been carried out at the 'top' CERN SPS energy of 160 A GeV, the intermediate range from $\sim$11 to 160 A GeV essentially has been 'terra incognita'. Only recently, experiments have been carried out at

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the CERN SPS for 40 and 80 A GeV [7,8] and further experimental studies are foreseen at 20 A GeV and 30 A GeV [9]. The elementary question thus arises to what extend we might find signatures for an intermediate QGP state or do we just see strongly interacting hadronic matter [10–12]?

The experimentally measured K^+/π^+ ratio, which has been suggested to be a deconfinement indicator (see, e.g., [7,13] and references therein), shows a non-monotonic behaviour with a possible maximum between 11.6 and 40 A GeV. Such behaviour cannot be fully reproduced by different microscopic transport approaches as RQMD [14], HSD [2] and UrQMD [15] (for more details see, e.g., [16] and references therein). The statistical model [18] is in better agreement with the data, however, it cannot shed light on chiral symmetry restoration or the existence of a QGP since this model is based on hadronic degrees of freedom, which are even non-interacting (contrary to the dynamical picture of transport models). The failure of transport approaches—based on hadronic and quark-string degrees of freedom [17]—to reproduce the K^+/π^+ ratio has been interpreted in [2] as a possible indication for the formation of unbound quark matter at high baryon density reached in the initial phase of central Au + Au (or Pb + Pb) collisions.

Whereas the K^+/π^+ ratio is basically attributed to the midrapidity yields, it is important to look also at the full rapidity range and independently on pion and strange particle yields for a better understanding of the collisional dynamics. The recent high accuracy data from the NA49 Collaboration [7,8] allow to make a more conclusive comparison on this issue. In this work we study central nucleus–nucleus collisions within a microscopic transport approach—the ultra-relativistic quantum molecular dynamics (UrQMD) model (version 1.3)—and compare with the data from the NA49 Collaboration for central Pb + Pb collisions at 40, 80 and 160 A GeV. Also we make predictions for pion and strangeness production at 20 A GeV.

The UrQMD transport approach is described in Refs. [19,20] and includes all baryonic resonances up to an invariant mass of 2 GeV as well as mesonic resonances up to 1.9 GeV as tabulated in the PDG [21]. For hadronic continuum excitations we employ a string model with meson formation times in the order of 1–2 fm$/c$ depending on the momentum and energy of the created hadrons. The transport approach is matched to reproduce the total nucleon–nucleon, meson–nucleon and meson–meson cross section data in a wide kinematical regime [19,20]. We note, that uncertainties remain with respect to the differential spectra in rapidity y and transverse momentum p_T, that are not sufficiently controlled by experimental data especially when short-lived resonance states are involved in the reaction. At the high energies considered here the particles are essentially produced in primary high-energy collisions by string excitation and decay, however, the secondary interactions among produced particles (e.g., pions, nucleons and excited baryonic and mesonic resonances) also contribute to the particle dynamics—in production as well as in absorption. In transport calculations all global symmetries like baryon number, charge and strangeness are strictly conserved as well as energy and momentum in each individual reaction.

Before coming to the results for central nucleus–nucleus collisions it is instructive to look at the UrQMD results for π^-, $K^\pm$ and $\Lambda(+\Sigma^0)$ rapidity spectra from pp collisions at the same bombarding energies per nucleon. The calculated rapidity spectra (normalized to the total pp cross sections) are shown in Fig. 1 for π^-, $K^\pm$ and Λ's at 20, 40, 80 and 160 GeV, respectively. One observes a smooth increase with energy of the π^- and K^+ spectra, both in magnitude and width. This increase with energy is more pronounced for the antikaons, which show a significantly smaller width in rapidity than the K^+ mesons. On the other hand, the $\Lambda(+\Sigma^0)$ midrapidity spectra are almost constant from 40–160 GeV while the width in rapidity increases substantially with energy. These general tendencies have to be kept in mind when interpreting the calculated results from central nucleus–nucleus collisions (see below). Furthermore, related differential experimental spectra would be highly welcome to shed some light on the dominant 'elementary' production process of pions and strange hadrons at these energies.

We continue with the related results for pions, kaons, antikaons and hyperons from A + A collisions and start at the highest bombarding energy of 160 A GeV. A comparison of our calculations for the most central (5%) Pb + Pb collisions at 160 A GeV with the data from Refs. [7,8] is shown in Fig. 2 for π^-, K^+, K^- and $\Lambda(+\Sigma^0)$. We note that the centrality of the reactions has been determined by a comparison of our calculations to the energy distribution in the

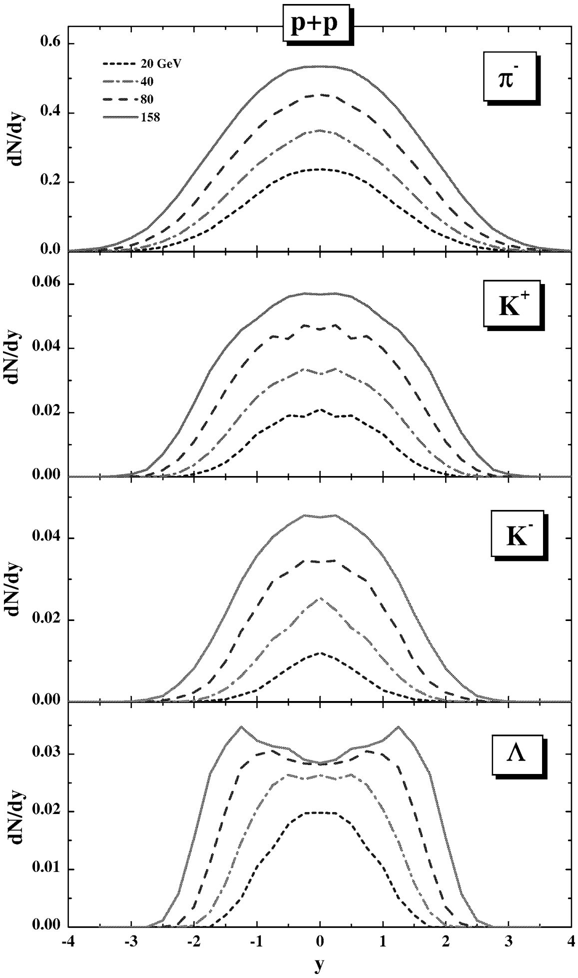

Fig. 1. The rapidity distribution of π^-, K^+, K^- and $\Lambda(+\Sigma^0)$ particles in pp collisions at 20, 40, 80 and 160 GeV calculated within the UrQMD model.

experimental Veto-calorimeter from NA49. It is seen that the spectral shape is rather well reproduced, however, the π^- yield is overestimated by $\sim$17%, whereas the K^+ and K^- spectra are underpredicted by $\sim$15% and $\sim$6%, respectively. The $\Lambda(+\Sigma^0)$ rapidity distribution is on the upper level of the experimental error bars. Though it has been claimed in Ref. [22], that a QGP might have been seen, the comparison of the hadron resonance/string approach with the data on $\pi^-, K^\pm, \Lambda(+\Sigma^0)$ rapidity distributions does not show clear signs of new (i.e., partonic) degrees of freedom at this energy. This finding essentially agrees with independent studies in the HSD transport approach [23,24].

We now step down in energy to the intermediate regime that has not been investigated experimentally so far. The data of the NA49 Collaboration for Pb + Pb at 80 A GeV [7] for $\pi^-, K^+, K-$ and $\Lambda(+\Sigma^0)$ are shown in Fig. 2 (3rd column) and compared to our calculations for the central (7%) events. Here we again observe an overestimation of the π^- yield by $\sim$20%, a very good description of the K^- rapidity spectra and a reasonable agreement with the data for the $\Lambda(+\Sigma^0)$ rapidity distribution. The K^+ yield falls off in the calculation by $\sim$17% such that the experimental K^+/π^+ ratio is underestimated by $\sim$30% from the UrQMD calculations. The situation is similar at 40 A GeV for the central (7%) collisions of Pb + Pb (cf. Fig. 2—2nd column) where K^- and $\Lambda(+\Sigma^0)$ rapidity distributions are well described, the K^+ yield is underestimated by $\sim$15% while the π^- spectrum from the calculations is too high by about $\sim$25%.

We note in passing that a simple strangeness counting rule, i.e., $N_\Lambda + N_{K^-} \simeq N_{K^+}$, does not hold in our case since the Λ yields include the decay from Σ^0 and in the total strangeness balance also K^0, $\bar{\Lambda}$, $\overline{\Sigma}$ etc. (with K^+) and $\Sigma^\pm$ as well as Ξ's and Ω's have to be considered, too.

Our predictions for the 7% most central Pb + Pb collisions at 20 A GeV, that will be measured at the SPS [9] and possibly in more detail at the future GSI facility [6], are shown in Fig. 2 (1st column) for π^-, K^+, K^- and $\Lambda(+\Sigma^0)$. Following the trend from the higher energies in Fig. 2 we expect also to overpredict the π^- yield and to underestimate the K^+ cross section.

The question remains to what extend the deviation of our transport calculations from the data in Fig. 2 might indicate new physics or the traces from partonic degrees of freedom. To this aim in Fig. 3 we present the channel decomposition (fraction in %) for the final K^+ (upper part) and K^- yields (lower part) calculated for central ($b = 0$ fm) Pb + Pb collisions at 20, 40, 80 and 160 A GeV. In order to explain the results from Fig. 3 we note that initially $s, \bar{s}$ quarks are produced in high energy nucleon–nucleon collisions and later on in meson–baryon interactions via string excitations and decays. However, afterwards the strange particles (produced initially) participate in chemical reactions with flavor exchanges. Thus only a few percent of the

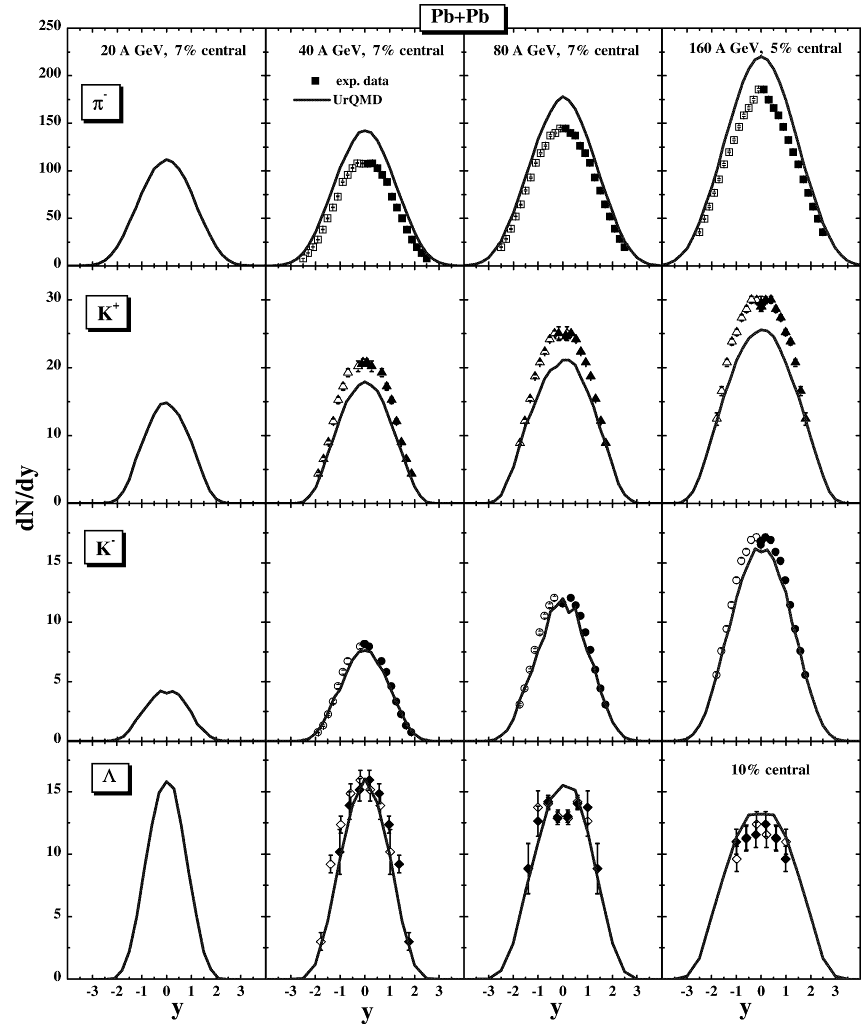

Fig. 2. The rapidity distribution of π^-, K^+, K^- and $\Lambda(+\Sigma^0)$ in 7% or 5% central Pb + Pb collisions at 20, 40, 80 and 160 A GeV calculated within the UrQMD model (solid lines) in comparison to the experimental data from the NA49 Collaboration at 40, 80 and 160 A GeV: the squares represent π^-, triangles—K^+, circles—K^- [7] and the diamonds indicate $\Lambda(+\Sigma^0)$ experimental data [8]. The full symbols correspond to the measured data, whereas the open symbols are the data reflected at midrapidity. Note, that the $\Lambda(+\Sigma^0)$ experimental data (as well as UrQMD results) at 160 A GeV correspond to 10% central Pb + Pb collisions.

'primary' kaons/antikaons remain unaffected by secondary inelastic interactions (cf. the lines denoted as 'BB string' in Fig. 3). Most of the final K^+ and K^- mesons finally stem from $K^{*\pm}(892)$ decays (lines 'K^* decay') which are either produced directly in string decays or by pion–kaon resonant scattering. About 2% of the final K^+ and $\sim$5% of K^- appear from the $\phi(1020)$ meson decays (lines 'ϕ decay'). The lines 'm^* decays' denote the fraction of final kaons and antikaons coming from higher mesonic resonance decays (i.e., $K^*(1410)$, $K^*(1680)$, $K_0^+(1430)$, $a_0(980)$, $f_0(980)$, etc.). At the SPS energies considered here only a small fraction of the final kaons/antikaons can be attributed to baryonic resonance decays ('B^* decays'). This fraction slightly increases when lowering the bombarding energy. About 15–20% of K^+ and 20% of K^- stem from meson–baryon string decays ('mB string') excited in energetic secondary meson–baryon interactions that do not longer participate in further inelastic reactions. Note, that in the channel de-

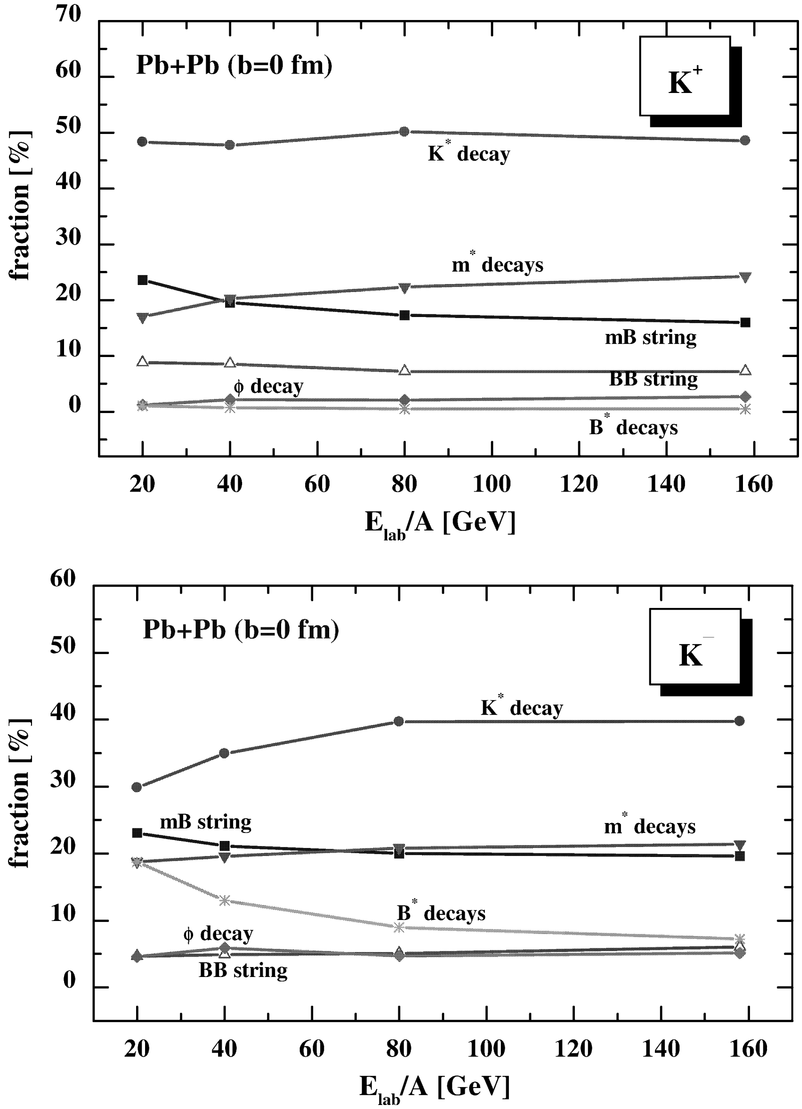

Fig. 3. Channel decomposition for the final K^+ (upper part) and K^- yields (lower part) calculated within UrQMD for central ($b = 0$ fm) Pb + Pb collisions at 20, 40, 80 and 160 A GeV.

noted as 'mB string' the kaon/antikaon–baryon collisions are also counted.

The picture, which emerges from the interpretation of Fig. 3, thus is as follows: only a small fraction of kaons/antikaons from energetic initial collisions survives the hadronic rescattering phase during the expansion of the fireball. Most of the final strangeness yield emerges after rescattering—shifting s quarks from mesons to baryons and vice versa—thus providing a very distorted picture on the initial strangeness production mechanism and the elementary degrees of freedom involved. Thus the $K^\pm$ and $\Lambda(+\Sigma^0)$ spectra do not allow for stringent conclusions on the initial phase of high energy density. On the other hand, these frequent flavor exchange reactions might be the reason why statistical models—employing chemical equilibration—seem to work reasonably well.

In summary, our detailed transport study with the UrQMD approach for central collisions of Pb + Pb at 20, 40, 80 and 160 A GeV has shown that the UrQMD model—involving string as well as hadronic degrees of freedom—reasonably describes the data from the NA49 Collaboration, however, systematically overpredicts the π^- yield by $\sim$25%. On the other hand, the K^+ yield is underestimated by $\sim$15–20% from 40 and 80 A GeV while the K^- yields are in a good agreement with the data for all energies. The $\Lambda(+\Sigma^0)$ multiplicities are found to roughly reproduce the data for all energies. The explicit channel decomposition of the final $K^\pm$ suggests that the kaon/antikaon rapidity spectra do not allow to determine the effective degrees of freedom—either partonic or string/hadron like—in the initial phase of the reaction due to the strong hadronic interactions in the expansion phase of the system.

The systematic overprediction of pions and underprediction of K^+ mesons might suggest that the hadron/string approach systematically fails in the energy regime from 20–160 A GeV especially when looking at the K^+/π^+ ratio (cf. Refs. [23,24]). Such a 'failure' might indicate the presence of partonic degrees of freedom in the initial phase of the collision and/or reflect a partial restoration of chiral symmetry [2]. However, some cautious remarks appear necessary: presently it is not clear if all the differential hadronic reactions employed in the transport calculation are sufficiently controlled by experimental data. This is even obvious for reactions involving short-lived resonance states. Thus it might well be that the $\leqslant$20% differences found in comparison to the NA49 hadron spectra could be attributed to uncertainties in hadronic cross sections or string fragmentation functions. Some further theoretical work and related data on the 'primary' NN and πN reactions will be necessary to clarify this presently open issue.

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